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THE ESTIMATION OF AIRPLANE PERFORMANCE FROM WIND TUNNEL TESTS ON CONVENTIONAL AIRPLANE MODELS.

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For nearly fifteen years wind tunnels have been in use as an invaluable tool of the airplane designer, and no move in the calculation of a new airplane is ever made today without reference to data obtained in the laboratory. The process of calculating performance by the accepted methods is one of summation of elementary resistances determined from the records of wind tunnel experiments on model airfoils, struts, fuselages and other parts, and in the evaluation of interferences between those parts, too, wind tunnel figures are relied upon.

Although it has been an increasingly common practice to build wind tunnel models of complete airplanes and to use the results obtained in testing them for the prediction of balance, stability and control characteristics, attempt to predict performance characteristics directly from the same tunnel test has been infrequent, as there are several obvious sources of error in any such calculation. The slipstream effect does not appear in a wind tunnel test. The model is not an exact representation of the completed airplane, as it would be practically impossible to simulate to scale all of the fittings and wires used on the airplane, and, even if those minute parts were made with the utmost faithfulness and included, the scale effect in their resistance would be so enormous as probably to cause an error greater than that to which their complete omission leads. Even on some of the parts that are included, such as the interplane struts, the absolute dimensions are so small as to bring the values of Reynolds number for those members down into a region where coefficients of resistance change very rapidly with small changes of speed or scale, and it is scarcely worth while trying to reproduce accurately such members, for example, as struts of streamline section.

Serious as these difficulties are, it is yet true that the total error from all sources in a performance prediction from a test of a conventional model is likely to be more a function of the general type of airplane than of the particular design, and the ratios between the performance so calculated and that actually obtained from the airplane on flight test may be expected to lie within a comparatively narrow range for all airplanes of generally similar type. With a view to determining the magnitude of these correction factors and the range of their variations, an extended series of performance calculations have been made for a series of conventional models, which have been tested in the past four years at the wind tunnel of the Massachusetts Institute of Technology, and calculated performances have been compared with those actually determined for such of the airplanes as have been built and put through flight test.

The elements of performance calculated include the maximum speed, minimum speed, absolute ceiling, and rate of climb at sea level. In the case of minimum speed the comparison with flight test results is of little significance, as the difficulty of measuring minimum speed in flight is such that an accurate determination is not to be hoped for in the ordinary performance test. The model result is undoubtedly closer to the true minimum in most cases than is that determined in a test of the full size airplane. For the model the speed is of course calculated by the formula:

$$V_{min} = V_m \sqrt{\frac{W}{L_{m_{max}}\ s^2}}$$

where $L_{m_{max}}$ is the maximum lift of the model as tested, s the reciprocal of the scale ratio (24 in case the model is built to a scale of one-half inch to a foot), W the weight of the airplane, and V_m the wind speed in the tunnel.

Since the power output of an airplane propeller in level flight is equal to the product of the total drag by the speed, with an appropriate horsepower conversion constant, and the resistance of the airplane is proportional to the square of the speed, maximum speed is obviously given by the formula:

$$V_{max} = \sqrt[3]{\frac{375\ P\ \eta\ V_m^2}{D_m\ s^2}}$$

where D_m is the appropriate drag of the model, P the engine horsepower, η the propeller efficiency, and the other symbols have the same meaning as before, all speeds being given in M.P.H. In making the calculations tabulated in this paper the actual engine horsepower determined by test was used. The propeller efficiency was determined by making a preliminary estimate of the maximum speed, an estimate which may be very rough without entailing appreciable error in the final result, calculating the V/ND at which a propeller designed to give its peak efficiency at maximum speed of flight will work, and determining the maximum efficiency from Lieut. Diehl's (Reference 1) curves based on the propeller tests made by Dr. W. F. Durand at Leland Stanford Junior University. The model drag has to be found by trial, as it is, of course, taken at the angle of attack corresponding to maximum speed. It is necessary, therefore, to make a succession of approximations to the maximum speed, and to take the appropriate model drag for each one, continuing until a figure is found for which the maximum calculated by the formula just given agrees with the approximation on which the calculation was based.

The process of calculation is not a very tedious one, but it would nevertheless be desirable to simplify it still further, and that can be done by making the further assumptions that the maximum propeller efficiency always has a fixed value of 75%, and that the angle of attack at which the airplane flies at maximum speed is always that giving minimum total drag. The first assumption is obviously invalid, but is unlikely to introduce errors of more than 7% or 8% in the power, which would correspond to errors of less than 3% in the determination of maximum speed. The second assumption approximates closely to the truth in most cases, as the drag curve is very flat in the neighborhood of the minimum, and there can be a considerable change in angle of attack, and so in speed range, without much effect on the drag at a given speed. Obviously, the minimum drag, if it is in error at all, will always be too low, and it would therefore be expected that there would be a tendency to over-estimate the maximum speed when calculation is made by this simplified procedure.

The calculations have actually been made for 23 models, and the results are tabulated below, with some remarks on the model construction and on any special peculiarities of the airplanes. Except as otherwise noted, all the models have interplane struts and diagonal struts formed to streamline shape, and wires were omitted in all instances. All of the models were about 18 inches in span and were tested in the 4-foot wind tunnel at the Massachusetts Institute of Technology except as otherwise noted.

Table I.

Estimation of Maximum Speed.

Model	Model Speed	Test Speed	Est. Method I	Est. Method II	Test 1st	Test 2d	Remarks
VE7	30	124	109.5	110	1.13	1.13	Cable used for interplane bracing designed very clean otherwise.
VE7a	30	114	108	108	1.06	1.06	Streamline wire for interplane bracing.
DH4	30	123.7	125	125	.99	.99	Round struts used on model. Airplane contains much round wire and many exposed fittings.
T3	40	94.6	98.5	100	.96	.95	Much parasite resistance. Side radiator used.
MB3	30	152	145	140	1.05	1.09	Tail not exactly like model. Wing radiator used.
MB3a	30	140.6	145	142	.97	.99	Side radiators used. Much interplane bracing of streamline wire.
Mess.	30	96.7	89	88	1.09	1.10	Very few wires on airplane. Diagonal strut represented on model

Table I (Cont.)

Estimation of Maximum Speed.

Model	Model Speed	Test Speed	Est. Method I	Est. Method II	Test 1st	Test 2d	Remarks
NBS1	40	98.7	96.5	98	1.02	1.01	Much wire and many external fittings. Free air radiators in slipstream. 3-foot model tested in large wind tunnel.
TP1	40	125.3	120	119	1.04	1.05	Side radiators used.
PW1	30	146	154	153	.95	.95	Free air radiators (none represented on model).
TA6	40	115.2	114.5	114	1.01	1.01	Cantilever biplane. No wires in interplane bracing. Engine cowl on model not an exact representation. 3-foot model tested in large tunnel.
PG1	30	116.5	124	124	.94	.94	Fuselage unusually angular in form. Model comparatively rough in construction.
V40	40	144.5	132	130	1.09	1.11	Cantilever monoplane.
D8	40	115	112.5	109	1.02	1.05	Cantilever parasol monoplane with exposed strut.

Table I (Cont.)

Estimation of Maximum Speed.

Model	Model Speed	Test Speed	Est. Method I	Est. Method II	Test 1st	Test 2d	Remarks
CO1	30	117.7	116	116	1.01	1.01	Cantilever monoplane with some exposed struts. Wing covered with corrugated metal Free air radiator.
MS	30	85.3	80	79	1.07	1.08	Externally braced monoplane of parasol type. Bracing wires not represented on model, but model contained 4 short struts not actually on airplane.
JL6	30	111.2	96	98	1.16	1.14	Cantilever monoplane wing low on fuselage. No wires.
MB6	40	170	175	172	.97	.99	Several wires in slipstream.
CO2a	40	137	125	123	1.10	1.11	Streamline wire used. Reported speed based on single test.
TW2	30	99		100	.99	.99	Side radiators used. Some uncertainty about speed and power.
R3	30	191.1	186	182	1.03	1.05	Cantilever monoplane. Lamblin radiators, represented on model.

Table I (Cont.)

Estimation of Maximum Speed.

Model	Model Speed	Test Speed	Est. Method I	Est. Method II	Test 1st	Test 2d	Remarks
PS1	40	145.6	149	145	.98	1.00	Semicantilever parasol monoplane tested with landing gear retracted.
PS1'	40	129.8	137	134	.95	.97	Same airplane, landing gear down. Holes in fuselage on airplane to allow for retraction of wheels not represented on model.
			Mean		1.03	1.03	

In examining these tabulations and, in particular, the ratios of actual to calculated speeds, there are a number of points which should be kept in mind as likely to affect the values of those ratios. Obviously, in the first place, the ratio of actual to calculated speed will be highest, other things being equal, when the scale effect on the model is largest, or, in other words, when the model is small or the speed of test is low. The point is illustrated by the MB3 and VE7 at one extreme, the T3 and TA6 at the other. It might be expected, too, that the ratio would be high for airplanes with thick airfoil sections, as such forms are likely to show an exceptionally large scale effect on the minimum drag.

Secondly, it is apparent that the introduction on the airplane of parts not present on the model, and offering parasite resistance, would tend to decrease the ratio, which would therefore have a low value for airplanes braced with large amounts of external stranded cable, or other round wire. For the same reason, the ratio would tend to be low when fittings are crude in design or completely exposed above the wing surface, as those points are not represented in the wind tunnel. The DH4, with a ratio of less than unity, even though tested at 30 M.P.H., is a case in point, while the VE7a represents an opposite extreme. Conversely, it would be anticipated that a cantilever monoplane would show an exceptionally high ratio of speeds, as there are on the airplane practically no wires or other bracing members not represented in the test. The JL6 furnishes an instance of this, but the D8 gives a much lower ratio than might be expected.

Although the speed ratios from calculation by the more exact method range from .94 to 1.16, and by the more approximate one from .94 to 1.14, this disturbingly large variation can be largely accounted for if the points mentioned in the preceding two paragraphs, as well as other less important but equally obvious causes of the differences, are borne in mind. The mean deviations of the ratios from the average values, all the tests being thrown in together with no attempt to interpret or forecast the variations of the correction factors, were 4.9% and

5.0% by the two methods, respectively. As the methods are so nearly equal in accuracy, the use of the more complicated one seems unjustified. The mean deviation of the maximum speeds as determined by a formula derived by one of the authors (Reference 2) from the true maxima for this same group of airplanes was 6.7%. The direct use of the tunnel test thus gives results somewhat superior to those from the formula.

The assumption that no intelligence will be used in interpreting and applying the model test is, however, an obviously unfair one. To see what might be done by an experienced man, a member of the faculty at the Massachusetts Institute of Technology was requested to make, from an examination of the wind tunnel models and a knowledge of the appearance of the corresponding airplanes but without making any calculations or having access to the wind tunnel test data, an estimate of the probable ratio between the actual and calculated speeds in each case. The mean deviation of his estimates from the actual ratios was 4.1%, and in only one case did the error exceed 8%. As the man who made the experiment had never tried anything of the sort before, there is little doubt that the average error of prediction could be cut to below 2½% after a little practice.

The climbing powers, as well as the speed, can of course be predicted from a wind tunnel test. To determine the rate of climb at sea level as accurately as possible it is necessary, instead of using a single formula, actually to compute from the wind tunnel test the power required for several speeds of flight, employing the formula:

$$375\ P_{req} = \frac{D_m\ s^2}{V_m^2}\left(\frac{V_m^2\ W}{L_m\ s^2}\right)^{3/2} = \frac{D_m\ V_m}{s}\sqrt{\left(\frac{W}{L_m}\right)^3}$$

and, then, plotting a curve of power available, to find the point of maximum separation between the two and calculate the rate of climb at that point by the usual method. In getting the second curve, Lieut. Diehl's propeller efficiency curves, contained in the report to which reference has already been made, were used in combination with an allowance for the change of speed of the engine with changing speed of flight based on a mean curve published some years ago (Reference 3).

A rougher approximation was based on the assumption that the propeller efficiency under conditions at maximum climb is uniformly equal to 60%, and that the angle of attack for best climb is that of maximum L/D of the airplane as whole. If the propeller efficiency were independent of speed, the best climb would, of course, be secured under the condition which makes $\frac{L^{3/2}}{D}$ a maximum, but the variation of propeller efficiency with speed of flight results in the maximum climb actually being obtained at a considerably lower angle.

As before, calculations have been made by both methods for all airplanes for which the necessary data were at hand, and the results have been compared with the actual rates of climb as measured in flight test. The first part of Table II gives the figures. The remarks on the models are of course the same as in Table I.

Table II.

Estimation of Rate of Climb and Ceiling.

Model	Test	Initial Rate of Climb (ft. per min.) Est. Method I	Est. Method II	Test / 1st	Test / 2d
VE7	1070	975	930	1.10	1.15
VE7a	975	1040	1030	.94	.95
DH4	1000	1150	1160	.87	.86
T3	315	540	490	.58	.64
MB3	1930	2210	2110	.87	.91
MB3a	1235	1690	1660	.73	.74
Mess.	700	826	800	.85	.87
NBS1	391	630	560	.62	.70
TP1	750	860	830	.87	.90
PW1	1240	1370	1450	.91	.86
TA6	1040	1400	1370	.74	.76
PG1	925	1260	1260	.73	.73
V40	1585	1770	1780	.89	.89
D8	1500	1570	1470	.95	1.02
CO1	775	980	840	.79	.92
MS	700	565	390	1.24	1.79
JL6	580	640	560	.91	1.03
			Mean	.86	.93
		Ceiling.			
VE7	21200	19900	18400	1.06	1.15
VE7a	18900	21400	19600	.88	.96
DH4	17600	20400	19600	.86	.90
T3	9000	14300	13200	.63	.68
MB3	24900	27600	25000	.90	1.00
MB3a	21200	23300	20700	.91	1.02
Mess.	15600	18600	16500	.84	.95
NBS1	10000	13800	12900	.73	.77
TP1					
PW1	21000	22200	21000	.95	1.00
TA6	20600	24500	22600	.84	.91
PG1	16900	21500	20400	.79	.83
V40	25400	28600	26300	.89	.97
D8	22100	25200	23200	.88	.95
CO1	18400	19200	16500	.96	1.11
MS	16500	12800	11200	1.29	1.47
JL6	15900	15200	14200	1.05	1.12
			Mean	.84	.87

The variations in climb ratios are even larger than those in speed, ranging as they do from .58 to 1.24, and from .64 to 1.79, by the more complex and the simplified method, respectively. The highest figures are, however, for a "freak" case standing quite by itself. The mean deviations are 13.3% and 16.8%, respectively, but if the one freak case, which seems likely to be chargeable against some error in the specification of weight or power, is eliminated, these figures are reduced to 12.2% and 11.4%. Again, the method involving the larger number of assumptions seems about as satisfactory as the one in which more care was taken. Calculations of rate of climb by formula (Reference 2) gave a mean deviation from the actual rates of 17%. An experiment on the prediction of the ratios, identical with that made when maximum speeds were in question, reduced the mean error to 9.5%, and further partial trials with estimates made by men who had gained some experience, left little doubt that the mean error could be reduced below 8%. The same factors mentioned in the discussion of maximum speed enter in here and serve to explain these variations in part, but there are other points which help to account for the width of the spread of the figures. Scale effect is less important at large angles than at small as a rule, and parasite resistance is also of less relative importance under climbing conditions than at maximum speed, but the slipstream is vastly more important in its effect when climbing with full throttle, and it is probable that the variations in slipstream effect very largely account for the discrepancies here observed. It would be expected, therefore, that the ratios would be smallest for airplanes with an unusually large slipstream effect on resistance, or, in other words, for the airplane having a large amount of resisting surface behind the propeller, but not so placed as to be likely to be of much service in increasing the thrust, as it is, of course, well known that a properly shaped body close behind the central proportion of the propeller may do. The NBS-1 and the T-3 exemplify this. In general, the airplanes with free air radiators in the slipstream have low ratios.

Another possible explanation of a part of the variation is found in the difficulty of securing accurate measurements of rate of climb in flight test. While a complete performance test should serve to give a close approximation to the best of which the airplane is capable under standard conditions, some of the figures here included are the results of scattered or incomplete tests, including only a single climb or an incomplete series of climbs, and the percentage of error is likely to be considerably larger than in the measurement of actual maximum speed for the same airplanes.

To predict the absolute ceiling of an airplane from wind tunnel test it is necessary to make the usual assumptions of decrease in engine power with altitude, etc., so the further assumption was made that the ceiling is given in feet by the formula (Reference 2):

$$H = 40{,}000 \log_{10} \frac{HP_a}{HP_r}$$

HP_a being the horsepower available at maximum speed and HP_r being the minimum horsepower required at any speed, both taken at sea level. Two methods were used to find the power required and there were therefore two determinations of ceiling, as of speed and rate of climb. First, the power required curve drawn for estimating rate of climb was prolonged to include the minimum. This should give the most accurate estimate possible from the test. The more approximate method was use the power required already found for climb at the angle of attack corresponding to maximum L/D instead of the true minimum power found by plotting the curve. In the first case, the power available was the same as that determined in the course of the calculation of maximum speed by the first, and more complex, method. In the second method of finding ceiling, a uniform propeller efficiency of 75% was used.

Calculations have been carried out for 16 airplanes (ceiling tests were lacking on the others) and the ratios of actual to predicted ceilings found, and the results are included in Table II.

The variations in ceiling ratios, like those for climb, are large. The lowest figures are .63 and .68 for the complex and simple methods, while the highest are 1.29 and 1.47. The mean deviations from the average is 11.0% for the more careful method and only 11.6% for the simpler. For a third time, therefore, it appears that the gain by the use of the more careful and longer calculation is trivial. As in the case of climb, figures near the extreme are rare, the high values standing quite alone and relating to the same airplane which previously had to be dismissed as a freak case. The mean deviation of the ceilings estimated by formula (Reference 2) from the true ceiling is 15%. The excision of the M-S model reduces the mean deviation to 8.8 and 10.5% by the two methods based on the wind tunnel result, 10.8% for the calculation by formula. Trials at the prediction of the ratios, similar to those previously described, cut the mean variation to about 10%, with partial tests by men with more experience in this particular line indicating easy possibility of a reduction of mean error to about 5% or 6%.

The same reasons given for variations in maximum speed and climb apply to the variations in ceiling factor, the effect of added parasite and scale effect being somewhat less at the angle of attack at the ceiling than at maximum speed. An added element of uncertainty is the variation of engine power with altitude, which is different with engines of different types, especially in the case of "high compression" engines and the rotary types.

In conclusion, and in the light of the study here made and the figures here given, it appears that the wind tunnel test is a very useful tool in performance calculation, and that, at the very least, a wind tunnel test made on a conventional model for the investigation of stability and balance should be made to provide information on probable performance as well. If carefully applied, the prediction of performance from such a model test should be more accurate than the result secured from any formula, and should not compare very unfavorably with the product of the most exhaustive and careful computation by the usual process of summation of partial drags.

References.

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